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Environmental Security Technology Certification Program

ESTCP

Application of Statistically-Based Characterization Tools to the Former Erie Army Depot and Toussaint River Site for the ESTCP Wide Area Assessment Demonstration

ESTCP Project # 200325

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1. Introduction

The efficient characterization and remediation of U.S. Department of Defense (DoD) sites that are potentially contaminated with unexploded ordnance (UXO) remains a high priority for the DoD. The total land area that is potentially contaminated with UXO has recently been estimated to be as high as 10 million acres (> 4 million hectares). Characterization efforts to date have shown that for a typical site, the UXO contamination is contained within a small portion of the site, often amounting to only 10 to 20 percent of the entire area. Therefore, efficient site characterization should be focused on identifying the location and extent of these smaller potential target areas within specific sites. To achieve this goal, the DoD Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) engaged Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) to develop efficient and defensible, statistically-based approaches for characterizing UXO sites.

The ESTCP program has sponsored several demonstrations of UXO site characterization technologies under a Wide Area Assessment (WAA) project. This report focuses on the application of statistically-based tools to the northern Ohio region of Lake Erie associated with the former Erie Army Depot and the Toussaint River. Typically, transects are surveyed using magnetometer or other geophysical instrumentation designed to detect magnetic anomalies indicative of metal fragments that may be related to munitions use at a site. PNNL and SNL have developed statistical algorithms that create transect designs based on desired Data Quality Objectives (DQOs) and then identify potential target areas based on geophysical surveys conducted along these transects. These algorithms have been incorporated into Visual Sample Plan (VSP), a tool used for designing sampling programs and statistically analyzing environmental data.

The transect design tools in VSP provide a statistically defensible method for specifying the required number and location of transect surveys that cover a small proportion of a total study area (i.e., 1 to 3 percent) to identify target areas of a desired size, shape, and magnetic anomaly density. Once surveys are conducted, high density area flagging routines are applied, and anomaly density estimates are derived to separate potential target areas from areas that may require no further remediation. These tools, when used in conjunction with the other technologies supported under the Wide Area Assessment project, can support more efficient transfer of formerly used defense sites to the public or private domain, or transition of these sites to other uses. Specifically, these tools are used to

1. design geophysical transect surveys to locate potential target areas with agreed upon DQOs,
2. estimate magnetic anomaly densities across the site
3. delineate target area boundaries.

2. Site Information and Munition Use

The former Erie Army Depot was used for almost a half century (i.e., from 1918 to 1966) by the Department of the Army for testing and proof-firing of artillery and as an ordnance storage and issue center. While the Archive Search Report (ASR) documents the munitions that were used on the site, information that would allow development of estimates of the location and/or size of likely impact areas is insufficient. The ASR documents three target pads located on the shore along the southern portion of the Lake Erie study zone; these target pads are north of the documented firing line (Figure 1). According to the ASR, ordnance was fired from one of two locations along the southern firing line towards vertical targets located at the target pads along the shore. Munitions fired from the firing line would generally land in Lake Erie. Information obtained from local residents indicates that there may have been additional firing points located just north of the Toussaint River, but there was no mention of these firing points in the ASR. Some unsubstantiated information also suggests that there may have been munitions dumped from barges into the lake. However no information was available on the amount or distribution of such dumps, and attempts to verify these reports were unsuccessful.

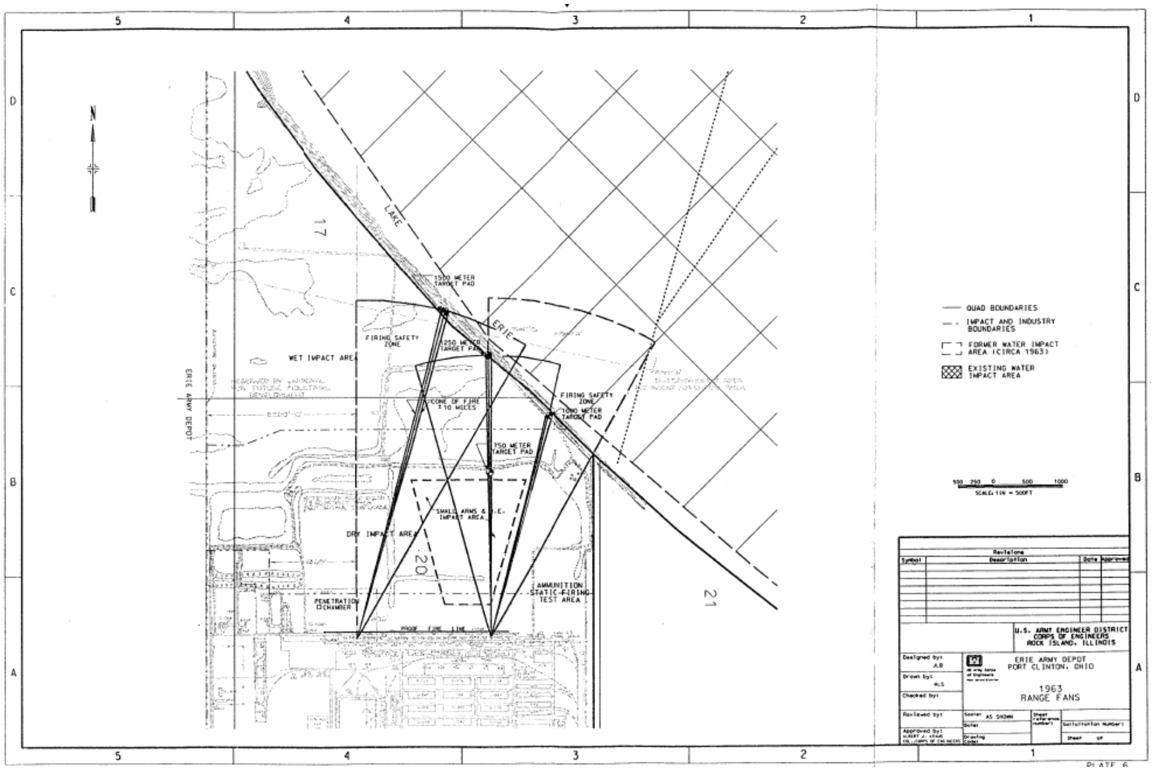

Figure 1. Image Taken from the Erie Army Depot ASR Showing the Relationship Between the Firing Line and the Three Target Pads Along the Shoreline.

3. Transect Design and Analysis Approach

PNNL was tasked to develop a transect survey design that would use an underwater towed-array system to detect magnetic anomalies along the floor of a water body. The transect survey design was developed with the aid of the VSP software. VSP, a statistical sampling software package designed by PNNL with funding from several government agencies, provides site investigators a simple-to-use, defensible method of gathering and analyzing environmental data. For this application, VSP's transect design, anomaly flagging, target-area delineation, and spatial anomaly density estimation and mapping modules were employed.

3.1. Transect Design Approach

To identify the spacing needed between transects to achieve a specified probability of traversing and detecting potential target areas of concern, the user must specify several operational parameters, including:

- width of the survey transect
- transect pattern on the site
- the size and shape of any target area that should be detected
- density and distribution of anomalies in the target area
- density of background anomalies at the site
- instrument false detection rate.

After the parameters are entered and a transect spacing is computed, the user can display the proposed transects with the map view option in VSP, and copy the coordinates of the proposed transects from the coordinate view or export the transect survey as an Economic and Social Research Institute Shapefile. A sensitivity analysis can be performed by evaluating the effects of changing the input parameters and managing the required DQOs. These methods and tools allow the project team to balance DQO goals against costs and other site constraints. Figure 2 shows the design dialogues in VSP, and an example of inputs that create graphs similar to the graphs displayed in Section 5.

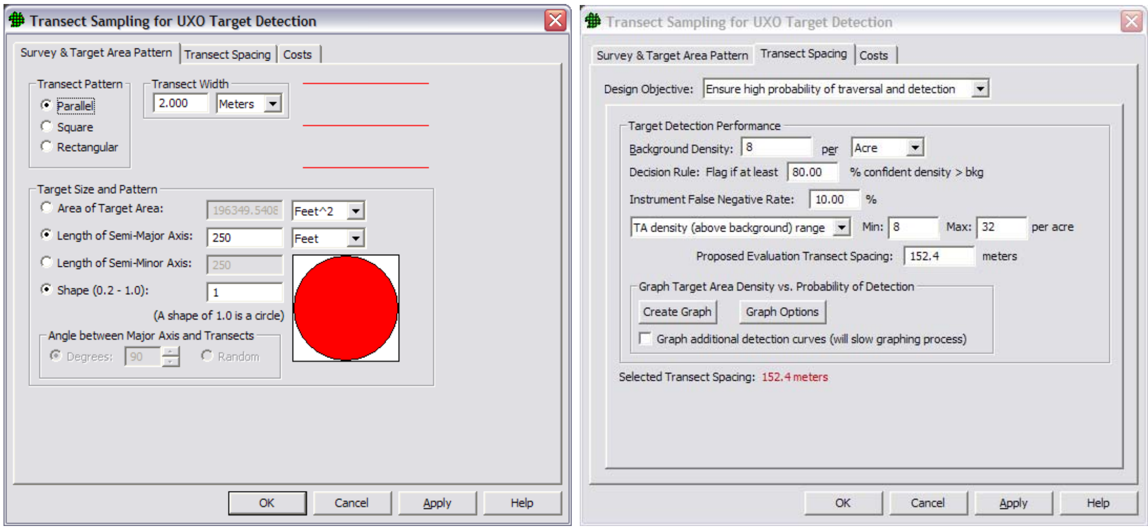

Figure 2. Design Dialogues in VSP Allow the User to Input Transect Pattern, Width and Target Area Size, Shape, and Orientation (left). Probability of detection curves can be displayed based on inputs and site assumptions (right).

3.2. Target Area Identification Approach

Once a transect design has been accepted and the geophysical survey completed, the surveyed data (i.e., the transect course-over-ground and anomaly location data) can be analyzed using VSP. PNNL and SNL have developed analysis algorithms to estimate anomaly densities from sparsely-spaced geophysical transect data. These spatially distributed estimates of anomaly density are then used to identify and delineate high-density objects in areas that were former target locations.

3.2.1. Flagging High Density Areas in VSP

To locate and mark suspected target areas or areas of interest (AOI) based on anomaly density patterns in the geophysical transect data, the user must select a critical density and an averaging window diameter. The critical density represents the threshold for flagging locations as AOIs. Locations with magnetic anomaly densities above the designated threshold are flagged as areas with a high potential of having been impacted by munitions. The window diameter specifies the size of the circular area over which the average density is computed. The VSP input dialogue for these parameters is shown in Figure 3. The target identification algorithm in VSP systematically moves a circular window with the selected diameter along each transect to calculate the number of anomalies found and the traversed area within each window (i.e., the black circular window in Figure 4). Those window intervals that have a density higher than the selected critical density are 'flagged' as AOIs. Figure 4 is a depiction of the algorithm process with the survey transects (light blue), associated anomalies (dark green), and circular window (black circle) that are needed for the VSP algorithm. The target area (red) and the site (light green) are shown in the picture for illustrative purposes only, as the location of the target area is usually not known.

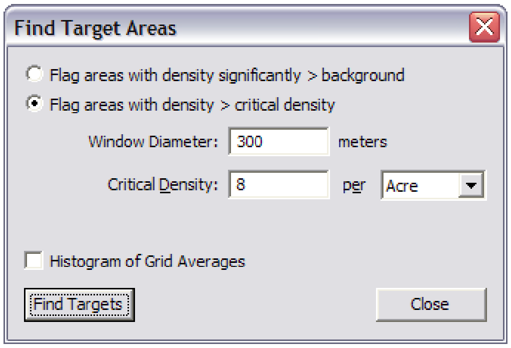

Figure 3. Find Target Areas Dialogue Used in VSP to Identify High Density Locations

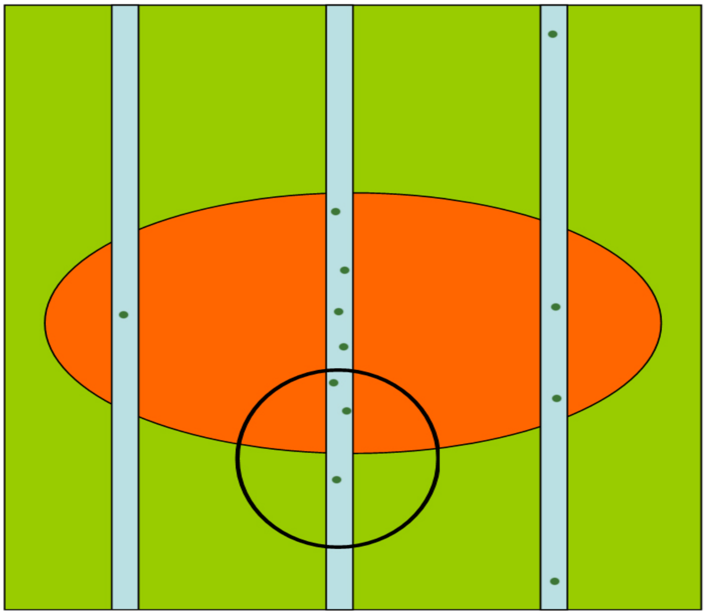

Figure 4. Visual Representation of the Analysis Algorithm Used in VSP to Identify High-Density Areas

Because there is often no prior estimate of the background density (i.e., anomaly density across the site in areas outside of target areas), VSP allows the analyst to examine the distribution of anomaly densities for the site based on a user-defined window diameter (see histogram in Figure 5). The user can then determine an optimum critical density or background density by identifying a possible inflection point in the distribution where the densities transition from background values to higher, potential target-area values. Background anomaly densities reflect what the magnetic anomaly densities at the site would be if the site had not been impacted by munitions. An additional method of obtaining an estimate of the background density distribution is to complete one or more transect surveys in an area that had no prior probability of munitions use.

The choice of window diameter and critical density is currently left to the VSP user. However, specification of this window diameter should consider the transect spacing and

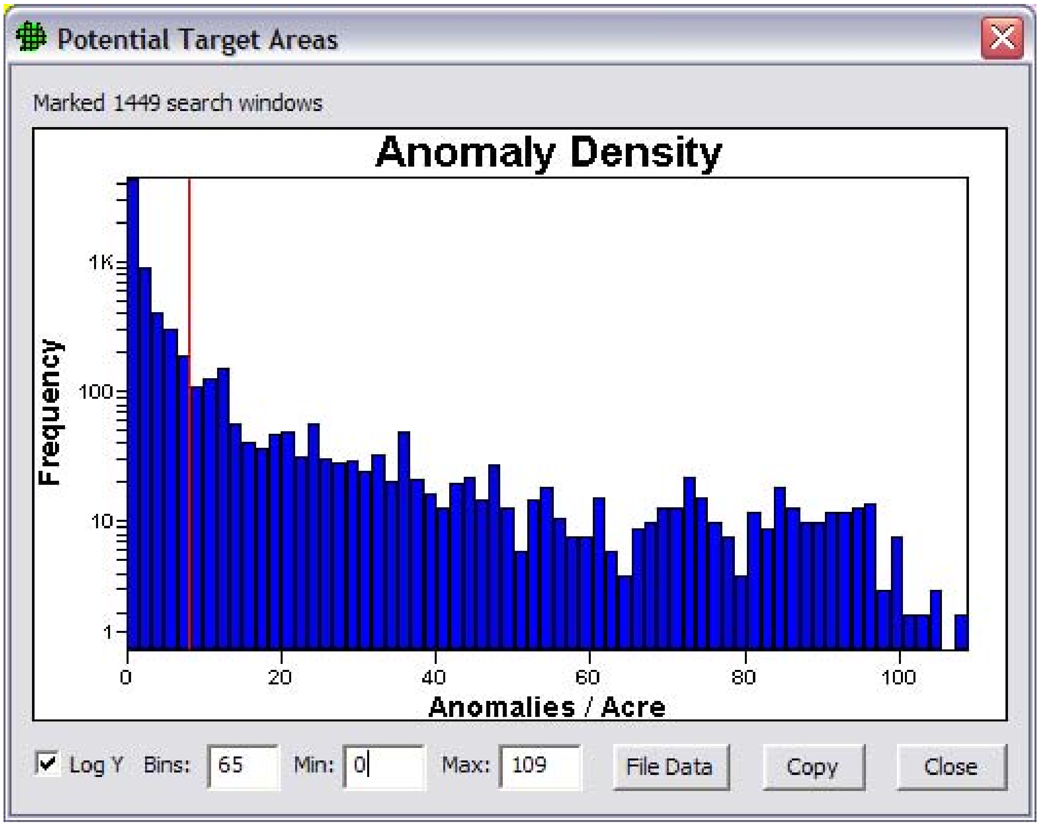

Figure 5. Example Histogram of the Window Densities Based on 155-m Spaced Transects with a 550-m Diameter Window

the assumed target area size and shape. Generally, the window diameter should not be any smaller than the spacing between transects or much larger than any large potential high-density regions on the site. Very small window diameters may result in a small amount of the surveyed area being within the window, which could result in high density values for areas containing only a few isolated anomalies. Conversely, larger window sizes encompassing more surveyed area require more anomalies within the window to meet the required critical density to be flagged as an AOI. For the analysis of the Lake Erie transect data, many different window sizes and critical densities were examined. A 550-m diameter window was the final value chosen for this analysis. This choice gives a window radius that is approximately the same as the spacing of the surveyed transects on the site (i.e., 330 m); therefore, it is almost the largest window size that would not include multiple transects. Using this 550-m window size, different critical densities were then considered. An evaluation of the Lake Erie anomaly data suggests that critical densities between 5 and 10 anomalies per acre are most reasonable.

Figure 5 shows a histogram of the window densities based on the complete Lake Erie transect survey. The critical density of 8 anomalies per acre (ApA) (the vertical red line in Figure 5) is within the area where the histogram shows an inflection point indicating the potential transition between background densities and those associated with possible target areas. After identifying this transition region, the final critical density was chosen to minimize the number of isolated and singleton flagged areas on the site.

3.2.2. Geostatistical Kriging for Identification, Delineation, and Estimation of High Anomaly Density Areas.

Kriging refers to a category of general least-squares regression techniques used in estimating unknown values. It is typically used to estimate values at unsampled locations for some spatially-varying characteristic. Kriging provides an unbiased estimate in that it attempts to have the residual errors sum to zero. As a regression technique, it also is designed to minimize the error variance of the estimates. The goal of the kriging estimation process as applied here is to identify areas with high concentrations of magnetic anomalies. These areas can then be delineated as AOIs that may represent former munition impact areas.

Kriging estimation relies on the spatial autocorrelation of the characteristic being sampled. Spatial autocorrelation refers to the level of similarity of data values from different locations in the study area. For the analysis presented here, we are concerned with the spatial autocorrelation of the magnetic anomaly density values as determined from the geophysical transect sampling. The autocorrelation of the characteristic being estimated is a key factor in the geostatistical estimation and must be modeled as part of the estimation procedure. Modeling of the autocorrelation is typically performed using semivariograms that depict how the variance in the data set changes with increasing separation distance between the data locations. These semivariograms are an integral part of the kriging process used to interpolate values for unsampled locations using surrounding data points.

Geostatistical estimation based on kriging techniques was used to provide estimates of site properties away from the transect locations to locations of the site domain that were not surveyed. Kriging estimates of two site properties were developed from the geophysical transect data. A probabilistic estimate of being within an impact area was developed using a technique known as Indicator Kriging (IK), which allows direct mapping of the probability of exceeding a critical magnetic anomaly density threshold across a site. Input for the IK technique was composed of an indicator variable developed from the geophysical transect data. This indicator variable had a value of “1” when the magnetic anomaly density was at or above the defined threshold, and a value of “0” when the density was below the threshold.

The critical density threshold used in defining the indicator variable represents the magnetic anomaly density level that is believed to signal a transition from non-impacted areas to impacted areas. Locations with density values above the critical threshold are considered AOIs that were likely affected by past munitions use at the site. Kriging of the indicator variable then provides a spatial representation of the probability of being above the critical threshold, which also defines the probability of being within an impacted area. These probabilities are defined on a percentage basis; high values indicate a high likelihood of being within an impacted area, while low values indicate a low likelihood that the area was impacted by past munitions use. Typically, a conservative probability value, such as 5 percent, is used as the guideline in delineating AOI boundaries from IK results.

The second site property estimated using kriging techniques was the magnetic anomaly density distribution. In this case, the estimated magnetic anomaly density at every location is the mean value of a Poisson distribution that defines the number of anomalies within an area. Density estimation provides additional information for AOI boundary delineation. A density contour is selected, and areas of the site where the estimated density exceeds this contour are defined as being within the impacted area. While this AOI delineation approach is more straightforward than the probability mapping approach, it is a deterministic approach and does not allow the decision maker any direct consideration of reliability in setting the extent of the target boundary. Magnetic anomaly density estimates were developed using the Ordinary Kriging (OK) algorithm.

As a part of data pre-processing undertaken prior to geostatistical analyses (kriging), an averaging procedure was applied to the raw magnetic anomaly location data. This procedure was similar to the moving window approach used within the VSP flagging routines; however, it operates on a grid-cell basis in which it computes the average anomaly density for each grid cell crossed by a sampling transect. Average density values are only computed for those cells actually crossed by a sampling transect as defined by the course-over-ground data provided by the geophysical survey team.

The anomaly density average is computed using a user-specified rectangular window around the cell of interest. Typically this window has its greatest dimension parallel to the transect direction. The average anomaly density is computed using the number of anomalies and total sampled area falling within the averaging window. The resulting anomaly density distribution is smoother than the original raw or unsmoothed magnetic anomaly data. The smoothed, more continuous grid cell values of anomaly densities resulting from this process then are used in the subsequent kriging estimates.
Figure 6 depicts this grid-based anomaly averaging routine. In Figure 6, an average anomaly density has been computed for the red grid cell taking into consideration all the anomalies (the black dots) and sampling transect area (the light blue swath) in the averaging window (the black rectangle).

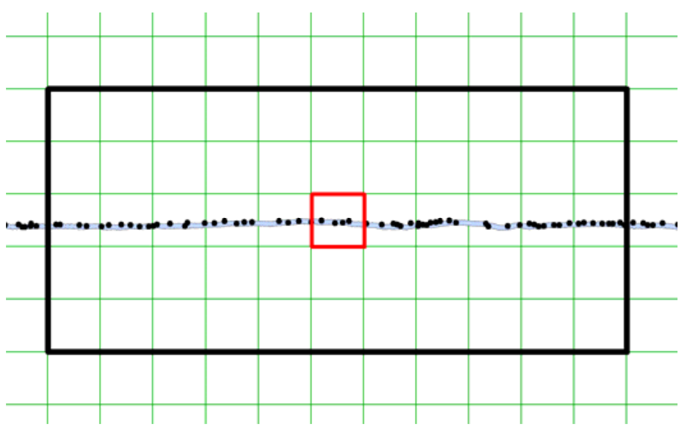

Figure 6. Schematic Depiction of the Anomaly Averaging Process Used in Kriging Data Pre-Processing. Grid cells are shown as green lines, the grid cell under consideration is the red square, the averaging window is the black rectangle, anomalies are black dots, and the sample transect is the light blue swath.

All anomaly density averaging for the Lake Erie transect data used 50-m square grid cells. This is the same grid cell size employed in the subsequent kriging analyses. For all the kriging estimations presented in this report, an averaging window of 550 m in the X direction (east-west) and 250 m in the Y direction (north-south) was used. This averaging window is large enough to provide sufficient smoothing of the anomaly densities, but small enough so that it considers only a single transect at a time, and does not overlap with nearby parallel transects.

4. Lake Erie Transect Design

ESTCP selected the military exercise area, which is identified in Figure 7 with the dark blue perimeter, and the additional area located to the west of the exercise area as the primary study zone to be surveyed. Development of a defensible transect survey design was a unique problem for this site because no information was available regarding the expected size and shape of the impacted area or the anomaly densities that might be expected given the historical use of the site. The potential size and shape of typical ground-based target areas can often be characterized by considering the munition used, the probable range and deflection error rates, and the fragmentation dispersion patterns (Hathaway et al. 2006). For the Lake Erie site, those parameters were not applicable. With very little information available about potential magnetic anomaly densities and target area sizes, the use of probability-of-detection curves typically employed for other site survey design demonstrations was not feasible for this site. Therefore, because of the lack of information about specific targets and munition use in the Lake Erie study zone, the transect design was developed to cover the maximum area possible within project budget and time constraints. All transects were oriented east-west as requested by the ESTCP program manager and survey team. Transects were designed to be collected using a marine towed magnetometer array with a total sampling swath (transect width) of 5 m.

Based on budget and time constraints, the original transects were spaced 165 m apart. This spacing would have required 1120 lineal kilometers in the preliminary study area and resulted in a 100 percent probability of traversing a 160-m diameter circular target area. This transect design was to be performed in two phases (see Figure 7). Phase 1 included the odd-numbered transects (i.e., every other transect) spaced 330 m apart on centers. Phase 2 included the remaining even-numbered transects. However, during Phase 1, it became apparent that the identified target area was very large, on the order of kilometers in length and width, so Phase 2 was deemed unnecessary and, therefore, was eliminated.

During the initial transect survey design, the West Sister sample area to the north of the original site (see the yellow bounded area in Figure 8) was excluded from the initial investigation area. Driven by the results from the initial survey, the West Sister sample area was later included to find the northern boundary of the large target area located inside the potential Lake Erie study zone and to identify munitions use around West

Sister Island. A draft action memorandum of the U.S. Army Corps of Engineers indicates that West Sister Island was used extensively by the U.S. Navy and Air Force and Army National Guard and Reserve Units for practice bombing.[1] Additionally, after the transect surveys were conducted, divers examined some of the identified anomalies and there were some intact munitions identified within transects surveyed near West Sister Island.

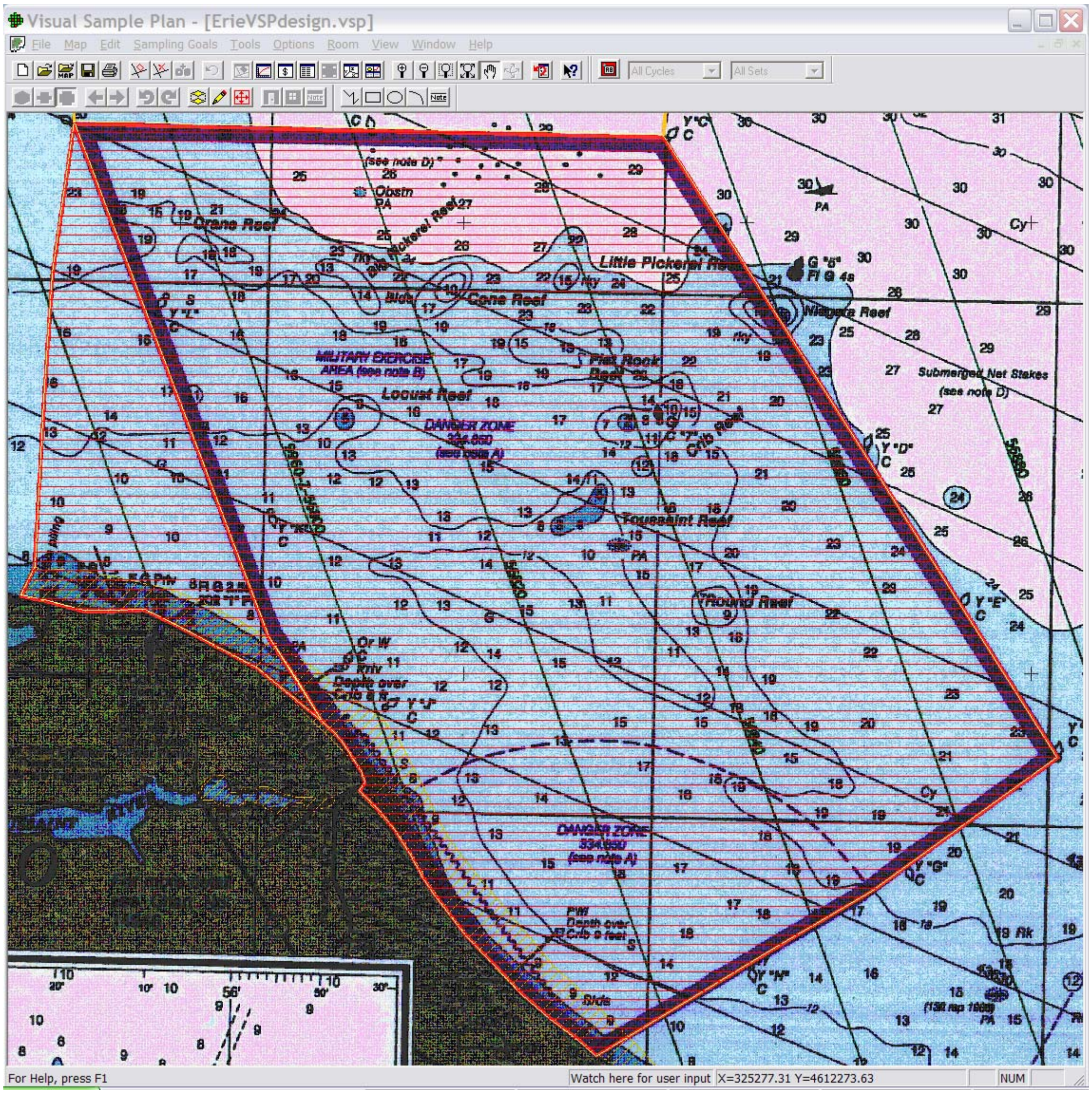

Figure 7. Lake Erie Survey Area with Transects (red lines) Placed East-West Over the Site. The West Sister sample area is located just north of this area as shown in Figure 8. The bathymetry is colored pink and blue on the map to represent a shift to deep water.

[1] U.S. Army Corps of Engineers, Louisville District. 2006. “Wet and Dry Impact Areas and West Sister Island, Former Erie Army Depot, Action Memorandum.” Working Draft, Louisville, Kentucky.

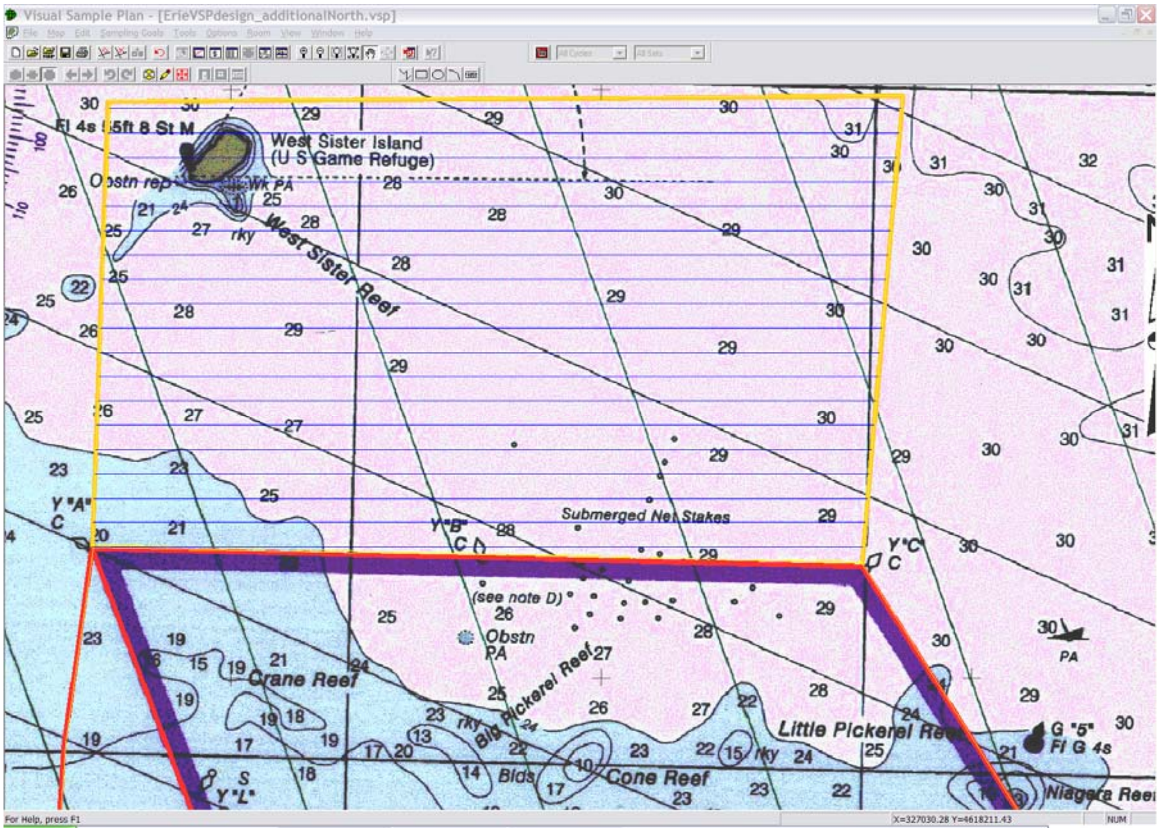

Figure 8. Transect Design for the West Sister Area (bounded by yellow line) Located at the Northern Boundary of the Lake Erie Survey Area. Transects are spaced 330 m apart on centers (blue lines). The bathymetry is colored pink and blue on the map to represent a shift to deep water.

The additional transects in the West Sister sample area were spaced 330 m apart on centers. This design was adopted to follow a similar, but independent, two-phase design as was planned for the Lake Erie study zone. Phase 1 included the odd-numbered transects with a spacing of 660 m on centers. Phase 2 would have included the even-numbered transects; however, it was not initiated because of a combination of weather conditions and water depths within the West Sister sample area.

5. Impact Area Identification

Figure 9 shows the actual traversed course-over-ground taken by the survey team. This figure shows how the transect spacing increased as they moved northward from the shore. As described previously, the transect spacing increased because the identified target area was extremely large and there was a desire to identify its northern boundary and, if possible within the project's time and budget constraints, to evaluate the area around West Sister Island. Table 1 summarizes the percent of the site area that was originally proposed for surveying and the percent actually covered by transect surveys.

Table 1. Summary of the West Sister and Lake Erie Study Zone Sample Areas by Phase and Actual Coverage

	Site Area (Acres)	Proposed Phase 1 & 2 Transect Coverage (Acres)	Proposed Phase 1 & 2 Percent Coverage	Proposed Phase 1 Transect Coverage (Acres)	Proposed Phase 1 Percent Coverage	Actual Transect Coverage (Acres)	Actual Percent Coverage
Lake Erie Study Zone	45,641	1,342.4	2.94%	671.2	1.47%	547.8	1.20%
West Sister	16,132	246.6	1.53%	123.3	0.76%	62.4	0.39%
Total Area	61,773	1589	2.57%	794.5	1.29%	610.2	0.99%

VSP was used to flag AOIs where the anomaly density was much higher than surrounding "background" areas as described at the end of section 3.2.1.
Figure **10** shows the flagged AOIs along the survey transects (the flagged areas are shown as clusters of solid red squares). The flagging routine for the VSP analysis used a 550-m window and flagged all areas with an anomaly density greater than 8 ApA . Other window sizes and densities were examined and provided similar results. The critical density of 8 ApA provided a good boundary around the central primary high-density area, with a few isolated singletons flagged regions at other locations on the site.

As mentioned in the previous section, there is documented use of West Sister Island as a target area, and intact munitions were identified during this study. However, based on the transect coverage around West Sister Island, which was limited to one transect just north of the island and one transect just south, there were no identified high-density AOIs in this region. Because of the limited coverage undertaken for this area, additional transect coverage would be needed before sufficiently confident estimates could be made regarding the likelihood of a target area in this region of the lake. Completion of the Phase 1 transects over the entire West Sister sample area also would validate that some of the larger unsampled regions do not contain high anomaly concentrations.

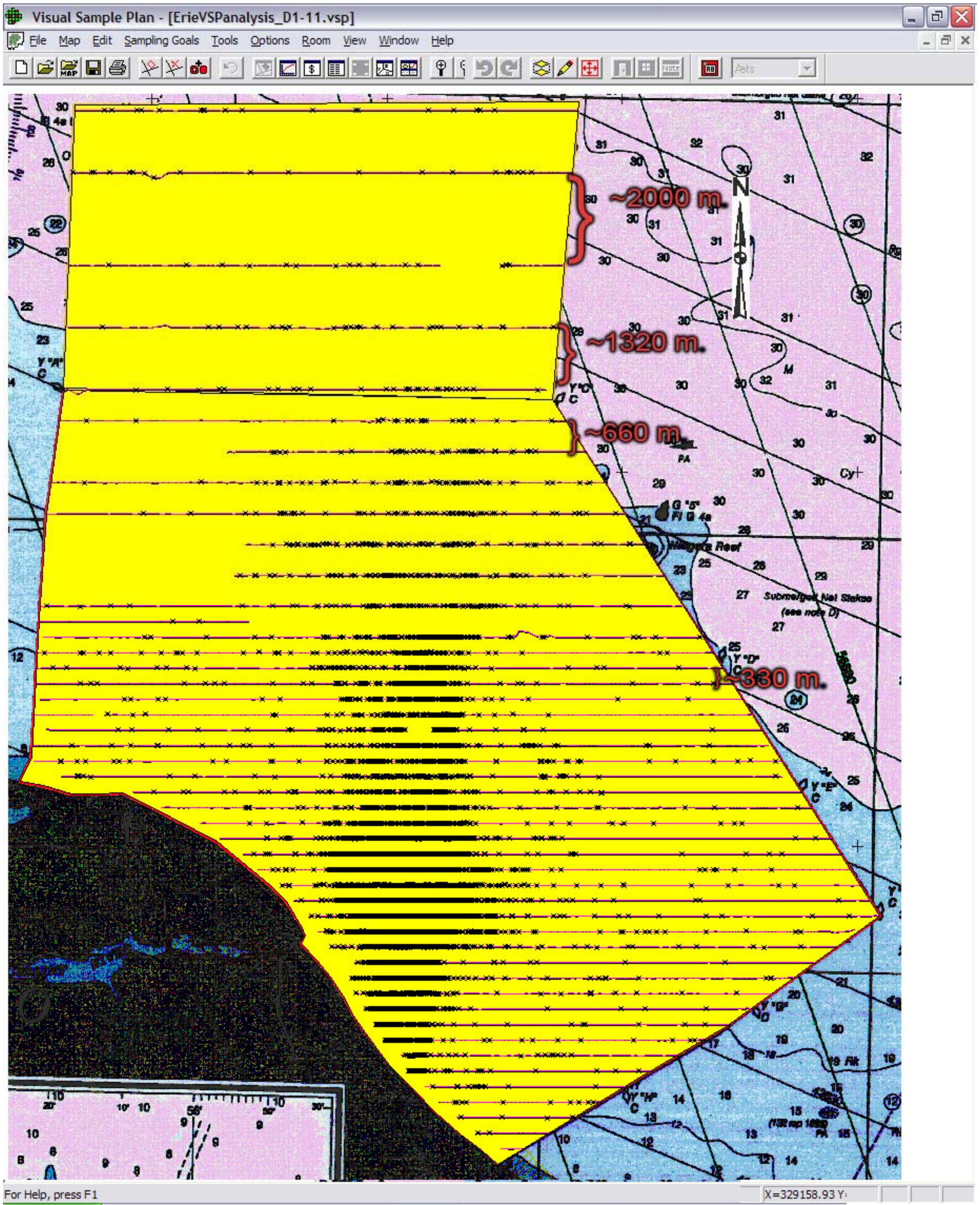

Figure 9. Image of the Actual Traversed Area Based on a 5-m Wide Transect with the Identified Anomalies (black symbols)

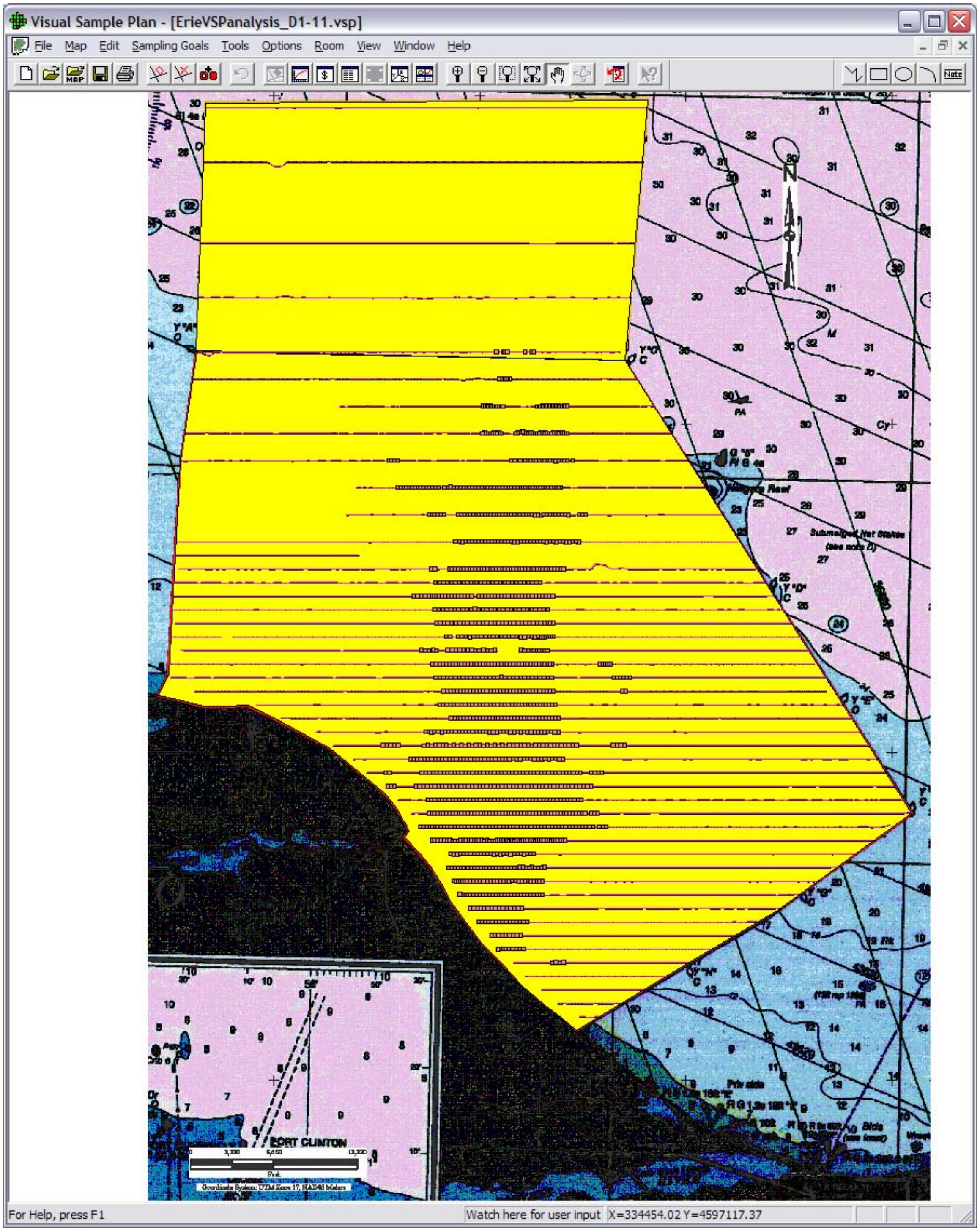

Figure 10. Flagged Areas of High Density Based on a Critical Density of 8 ApA and a 550-m Window

Figure 11 shows the IK probability map developed from the magnetometer transect data using an IK threshold of 8 ApA. The semivariogram model used in the IK is listed in Appendix A. In Figure 11, areas with a probability of 0.05 or greater of being above the 8 ApA threshold are indicated by color-filled probability contours. These areas were

included as part of the information used in determining the final boundaries for the AOI. The IK threshold value of 8 ApA was chosen based on the spatial pattern resulting from the implementation of different threshold values. This value is consistent with the 8 ApA used in the VSP flagging routine as well. The 8 ApA value was selected as the minimum value that did not generate a spatial pattern of the indicator variable, which contained many small isolated clusters in the smoothed anomaly data. The 8 ApA threshold value generated indicator variable spatial patterns with large contiguous, areas which are expected for former munition impact areas.

Both the flagging routine and the IK identified the same AOIs, and both were used to delineate the boundaries for those AOIs. The two AOIs shown in Figure 11 (designated A and B and formed by dark green polylines) represent the areas with the greatest concentrations of detected magnetic anomalies from the transect sampling. There are other small isolated color-filled areas shown in the IK results and isolated flagged areas that were not included in the delineated AOI. These are believed to be artifacts of the sampling and analysis based on the transect course-over-ground and the spatial distribution of anomalies. Additional sampling would need to be performed before definitive conclusions regarding these areas could be made.

Figure 12 presents the anomaly density estimates generated from the OK analysis. The semivariogram model parameters used in the OK analysis are listed in Appendix A. In Figure 12, areas with an anomaly density above 8 ApA are shown with color-filled contours indicating the estimated density. As in the previous figure, the identified AOIs are shown with dark green polylines. The general extent of the higher density areas reflect the pattern seen in the IK results (Figure 11).

As Figure 11 and Figure 12 show, the largest AOI (designated by the letter A) has an elongate form that has its longest axis along a north-south orientation. This direction is generally parallel to documented firing directions used at the Erie Army Depot. The highest magnetic anomaly concentrations are located in the southern half of AOI A, approximately 3 to 5 km from the firing line.

Table 2 presents general characteristics for each of the AOI identified in the kriging and flagging analyses. As seen in this table, the total AOI area is almost 13,000 acres, and the total anomaly count estimated from the kriging analysis is over 300,000.

Table 2. General Characteristics of the Identified AOIs. The second row (Transect Detected Anomalies) presents the total number of anomalies detected within the 5-m transect sample data; the Kriging Estimated Anomalies row reports the total number of magnetic anomalies for that area as estimated using Ordinary Kriging.

	AOI A	AOI B	Total
Area (acres)	12,571	236	12,807
Transect Detected Anomalies	4,683	30	4,713
Kriging Estimated Anomalies	332,447	1,568	334,015

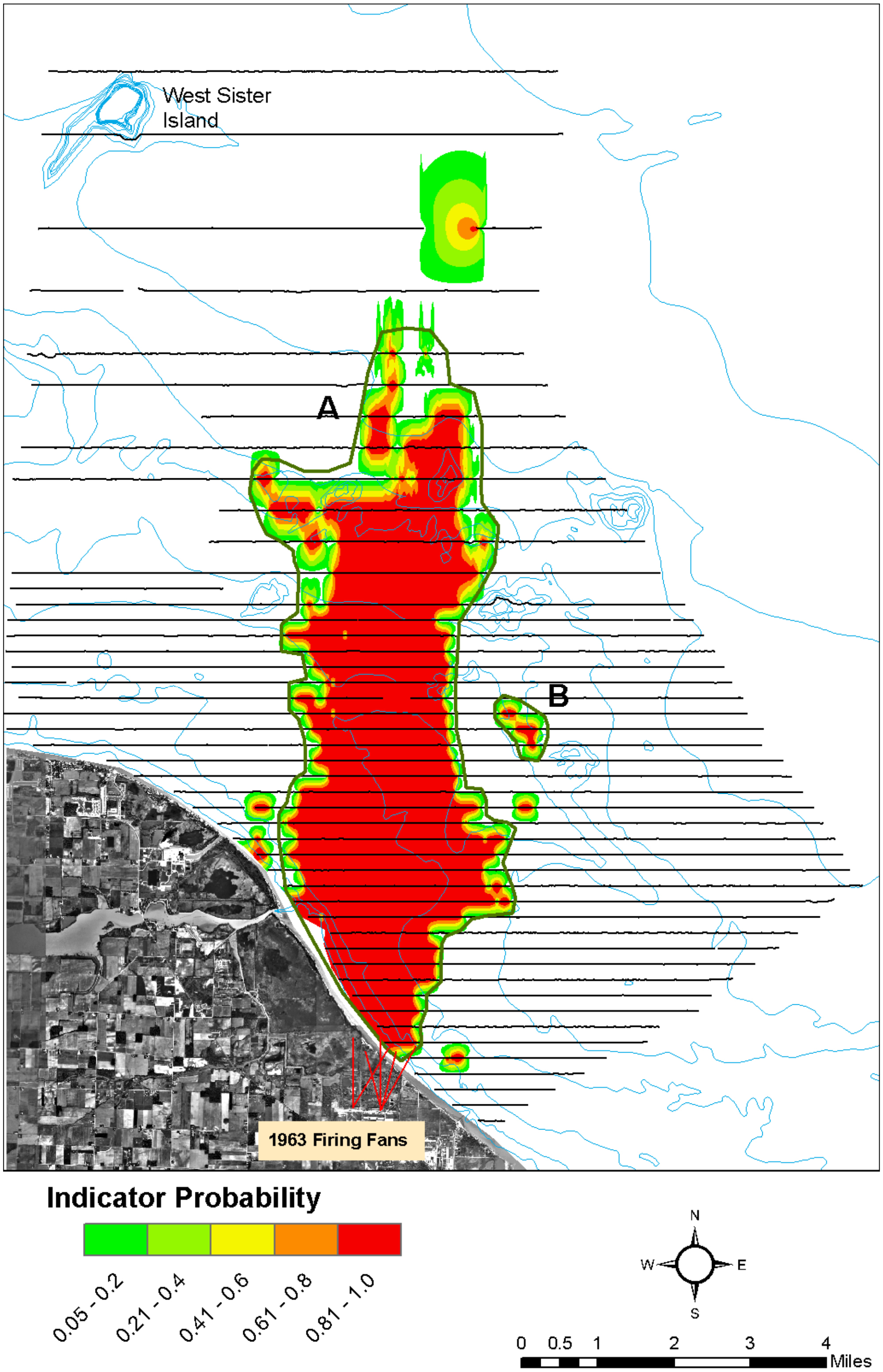

Figure 11. Indicator Kriging Results Showing Probability of Being Above 8 ApA. The dark green polylines define the AOIs (A and B); the black lines show magnetometer transects; and the light blue lines show the bathymetry contours.

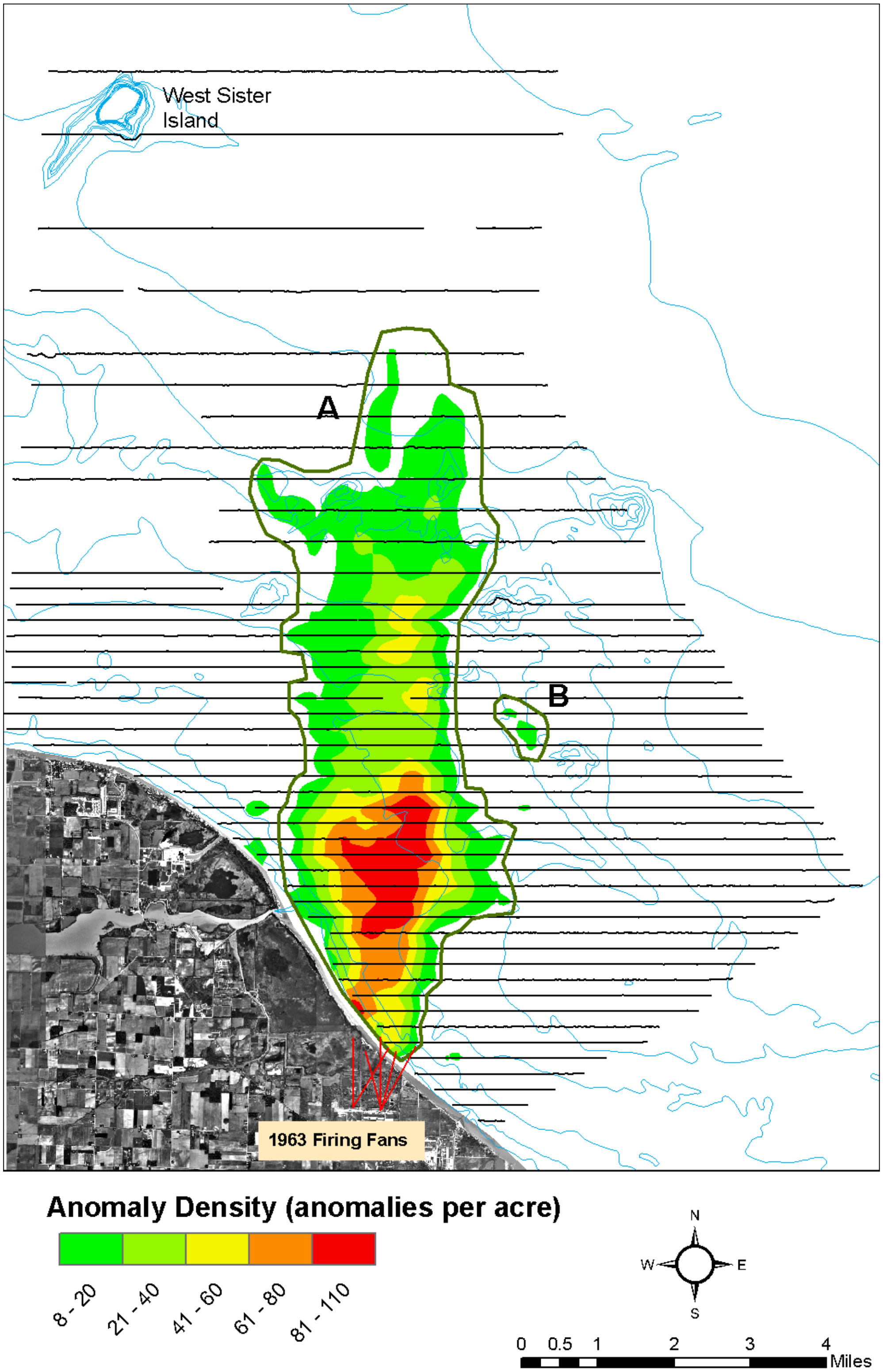

Figure 12. Ordinary Kriging Results Showing Magnetic Anomaly Densities. The dark green polylines define the AOIs (A and B); the black lines show magnetometer transects; and the light blue lines are the bathymetry contours.

6. Summary

Using magnetometer data collected from a statistically designed transect sampling scheme, VSP flagging routines and geostatistical analyses were used to identify locations with high magnetic anomaly densities that may represent concentrations of munitions test fired from the former Erie Army Depot. A total of 610 acres of geophysical transect data were distributed over the 61,700 acre study area representing a sampling coverage of about 1percent. Anomaly densities as high as 110 ApA were estimated from the geostatistical analysis using 50- by 50-m grid cells.

Two AOIs representing areas of high magnetic anomaly concentrations were identified through the VSP flagging and geostatistical analysis (Figure 11). Both AOIs are in line with the prominent firing directions used at the Erie Army Depot. The primary AOI (AOI A) is very large, covering over 12,000 acres with its longest dimension over 15 km in length. This AOI contains the highest anomaly concentrations and holds the majority of the total estimated anomaly count (Figure 12 and Table 2). A smaller AOI (AOI B) is located just east of AOI A, but it is significantly smaller in size compared to AOI A, covering only 236 acres with its largest dimension being approximately 1500 m in length. This AOI may be a “spill over” from AOI A because it appears to be in a deeper zone with a shallow area separating it from AOI A. Both of these AOIs are likely related to test firing activities at the former Erie Army Depot. Additional magnetometer transect data would be needed to further characterize the relationship between AOIs A and B and to determine whether they in fact represent one contiguous high anomaly density area.

7. References

Hathaway J, BL Roberts, SA McKenna, and BA Pulsipher. 2006. *Application of Statistically-Based Site Characterization Tools to the Pueblo Precision Bombing and Pattern Gunnery Range #2 for the ESTCP Wide Area Assessment Demonstration*. PNNL-16418, Pacific Northwest National Laboratory, Richland, Washington.

Appendix A

Variogram Model Parameters

This appendix presents the analytical model parameters (Table A1) used during the kriging analyses. Variograms from observational data were computed using a lag of 50 m and a lag tolerance of 25 m. Observational data consisted of anomaly densities expressed as AoA. Figure A1 presents a graphical representation of the observational data and the fit models.

Table A1. Variogram model parameters used for the Indicator Kriging (probabilities) and Ordinary Kriging (anomaly density estimates).

	Nugget	Model Type	Sill	Range (m)
Indicator Variable	0.002	Spherical	0.065	1,300
Anomaly Density	2.0	Gaussian	200	2,496

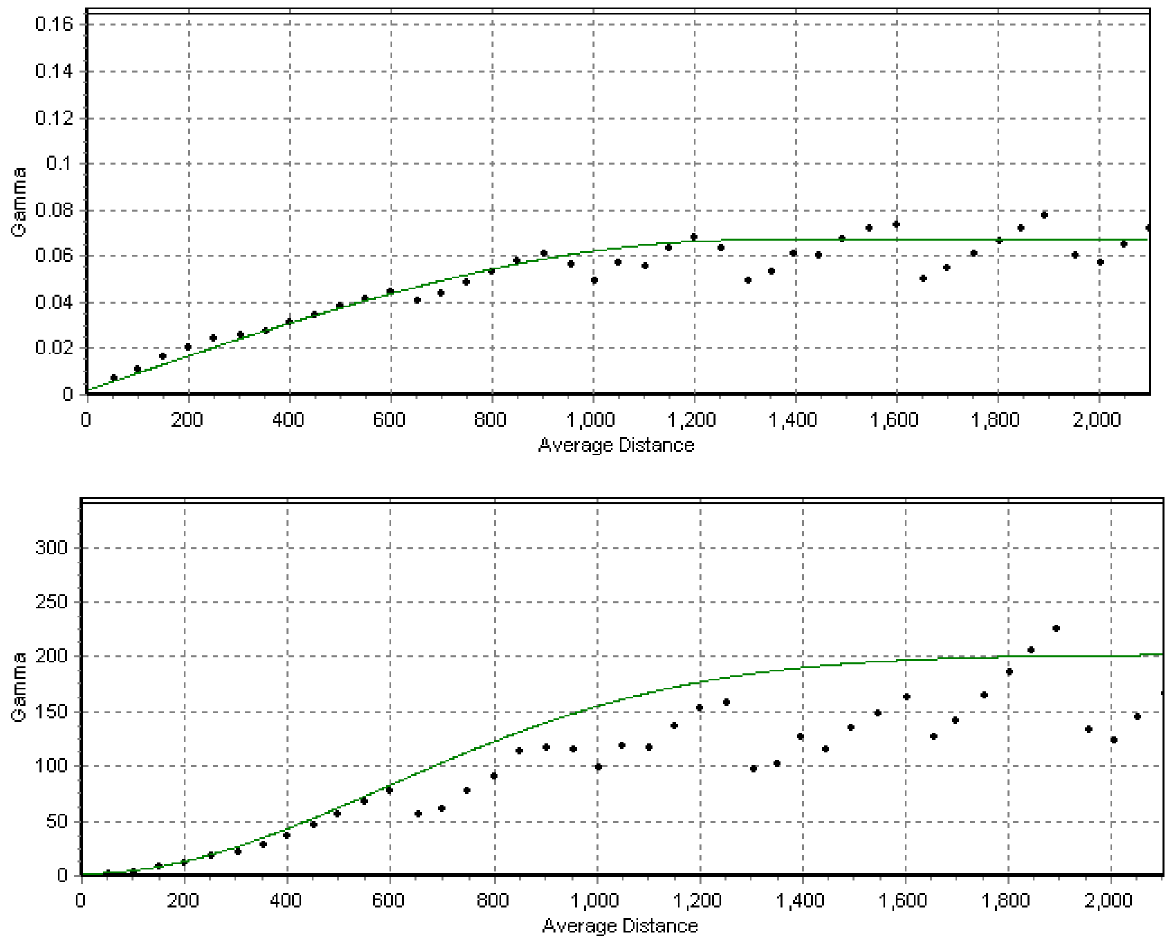

Figure A1. Empirical variograms (black dots) and respective analytical models for Lake Erie magnetometer transect data sets. Top plot is for indicator variable; bottom plot is for anomaly density where original data were in AoA.